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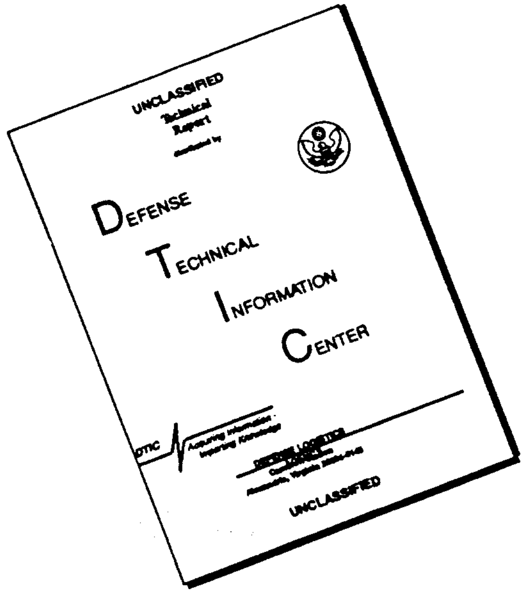

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AFOSR Final Project Report for the Grant:

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The grant was in support of a research program to explore the possibility of a microwave atomic clock based on an atomic fountain of cesium atoms. During the two year granting period, the following work was done:

1) A large magneto-optic trap in a vapor cell was constructed where over 4×10^{10} atoms were trapped at a density on the order of 10^{11} atoms/cm^3.[1] This work increased the number of atoms optically trapped by a factor of ~400 compared to previous work. The optical density of the atoms in this trap has a peak attenuation of e^{-175}.

2) In an invited review article, we examined the prospects for slow atom frequency standards.[2] Most of the systematic effects that limit the current accuracy of today's frequency standards decrease as the velocity of the atoms is reduced. We identified the one possible exception: collisions between ultra-cold atoms in an atomic fountain could induce a phase shift that would ultimately limit the accuracy of the fountain clock. We brought the problem to the attention of B. Verhaar, who began a series of calculations on the effects of low energy collisions.

3) We made the first frequency standard based on an atomic fountain of cesium atoms.[3] Earlier work such as our original atomic fountain [See M. Kasevich, *et al.*, Phys. Rev. Lett. **63**, 612, (1989)] and the French effort [Audion, *et al.* Europhys. Lett. **16**, 165, (1991)], can not be considered to be frequency standards since the magnetic fields were not adequately controlled. Our cesium fountain currently has a short term stability of $\sim3\times10^{-13}/\tau^{1/2}$, roughly an order of magnitude better than the PTB frequency standard.

In this same paper, we reported the measurement of the phase shift due to collisions between ~1 μK atoms in the atomic fountain. As one goes to lower temperatures, collisions would be dominated by the lowest orbital angular momentum partial waves, and this work was the first measurement of almost exclusively s-wave scattering of atoms.

The measured phase shift was larger than predicted by Verhaar and collaborators. In terms of a limitation of the accuracy of a clock, we suggested ways to reduce the effect without compromising the short term stability of the

clock. We also showed that the relative density could be accurately measured, an extrapolation of our measurements to zero density had an uncertainty of 3×10^{-14}. Based on our results, we feel that the absolute accuracy of an atomic clock based on a cesium fountain can approach $\Delta\nu/\nu = 10^{-16}$.

4) Using the data taken with our atomic clock, we interpreted the measured collisional frequency shifts using coupled channeled theory and a simple model of hyperfine coupled long range molecular states.[4] With this simple model we were able to extract the *sign* of the s-wave quantum mechanical scattering length. I believe this is the first time one has been able to extract the sign of the scattering amplitude in a collision experiment. These results are important in attempts to realize Bose condensation in ultra-cold atomic cesium vapor, since a stable Bose condensate demands a positive scattering length.

5) We are continuing to explore low energy collisions in the atomic fountain. (Achiem Peters has taken over the work begun by Kurt Gibble after Kurt left to join the faculty at Yale University.) Based on the observed large collisional cross-section and our calculations, we believe that the last excited bound state of the cesium molecule is very close to the dissociation limit. This has raised to possibility that a molecular state can be tuned through the dissociation energy with the application of an external field. Thus, it may be possible to change the sign of the scattering length by tuning an external magnetic field! We have preliminary results that show an interesting oscillation in the phase shift for the $F=1$, $m_F=+3$ state colliding with $m_F=0$ states. If this oscillation is real, then it should also appear in the $F=2$, $m_F=-3$ state and we are setting up to measure that phase shift. These measurements are delicate since the phase shifts correspond to a frequency shift on the order of 0.5 Mhz out of a microwave frequency of 9.2 Ghz.

References published during the course of this work:

1. Improved Magneto-optic Trapping in a Vapor Cell, (K.E. Gibble, S. Kasapi, and S. Chu), *Optics Letters* **17**, 526 (1992).

2. Future Slow Atom Frequency Standards, (K. Gibble and S. Chu), Metrologia **29**, 201, (1992).

3. A Laser-Cooled Cs Frequency Standard and a Measurement of the Frequency Shift due to Ultra-cold Collisions, (K. Gibble and S. Chu), Phys. Rev. Lett. **70**, 1771 (1993).

4. Cold collision properties derived from frequency shifts in a cesium fountain, (B. Verhaar, K. Gibble and S. Chu), Phys. Rev A **48**, R3429 (1993).